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(54) **SYSTEM AND METHOD FOR MAKING RENEWABLE FUELS**

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(57) **ABSTRACT**

Multiple catalytic processing stations enable a method for producing volatile gas streams from biomass decomposition at discrete increasing temperatures. These catalytic processing stations can be programmed to maximize conversion of biomass to useful renewable fuel components based on input feedstock and desired outputs.

23 Claims, 10 Drawing Sheets
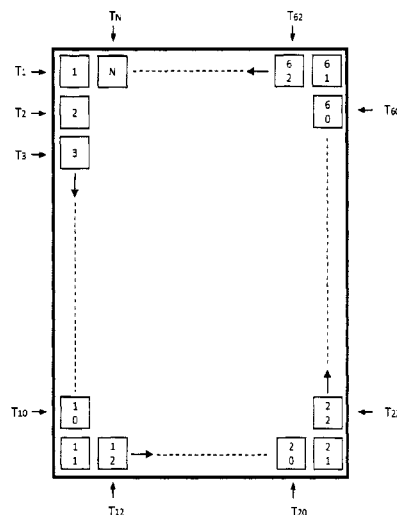
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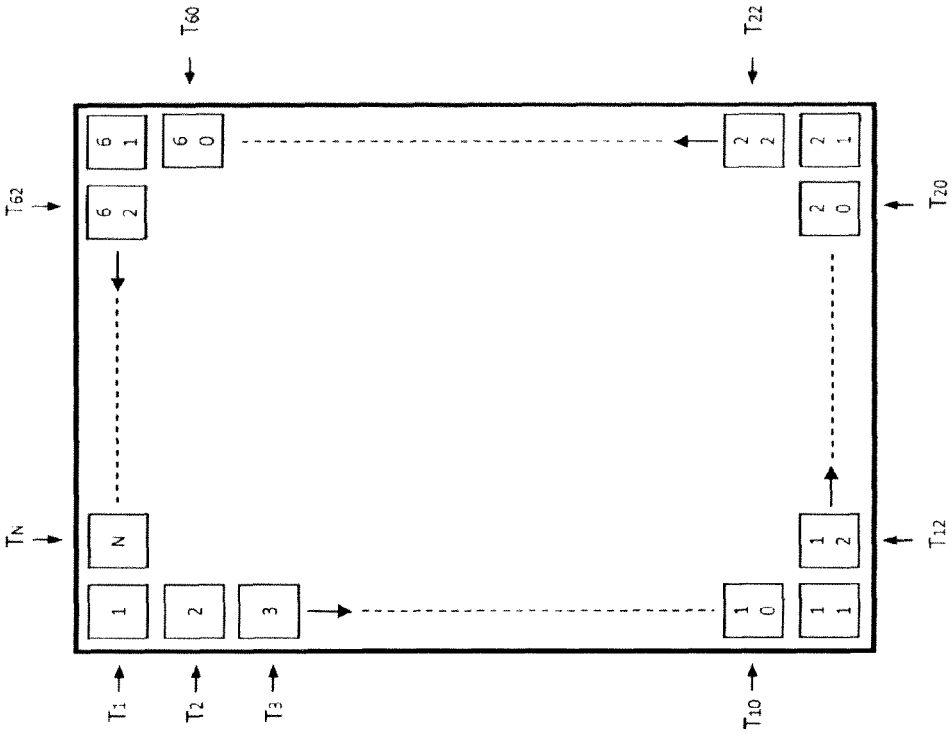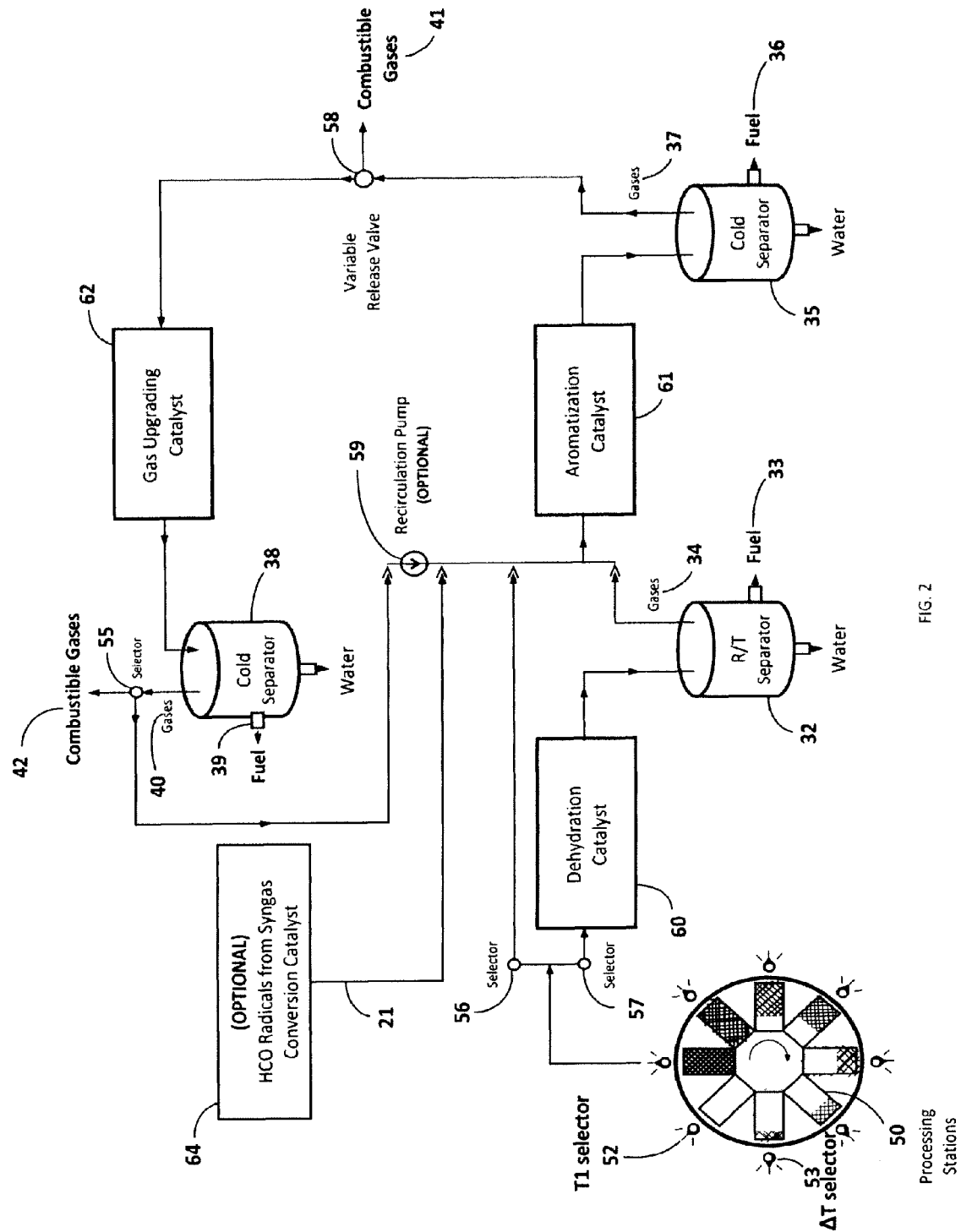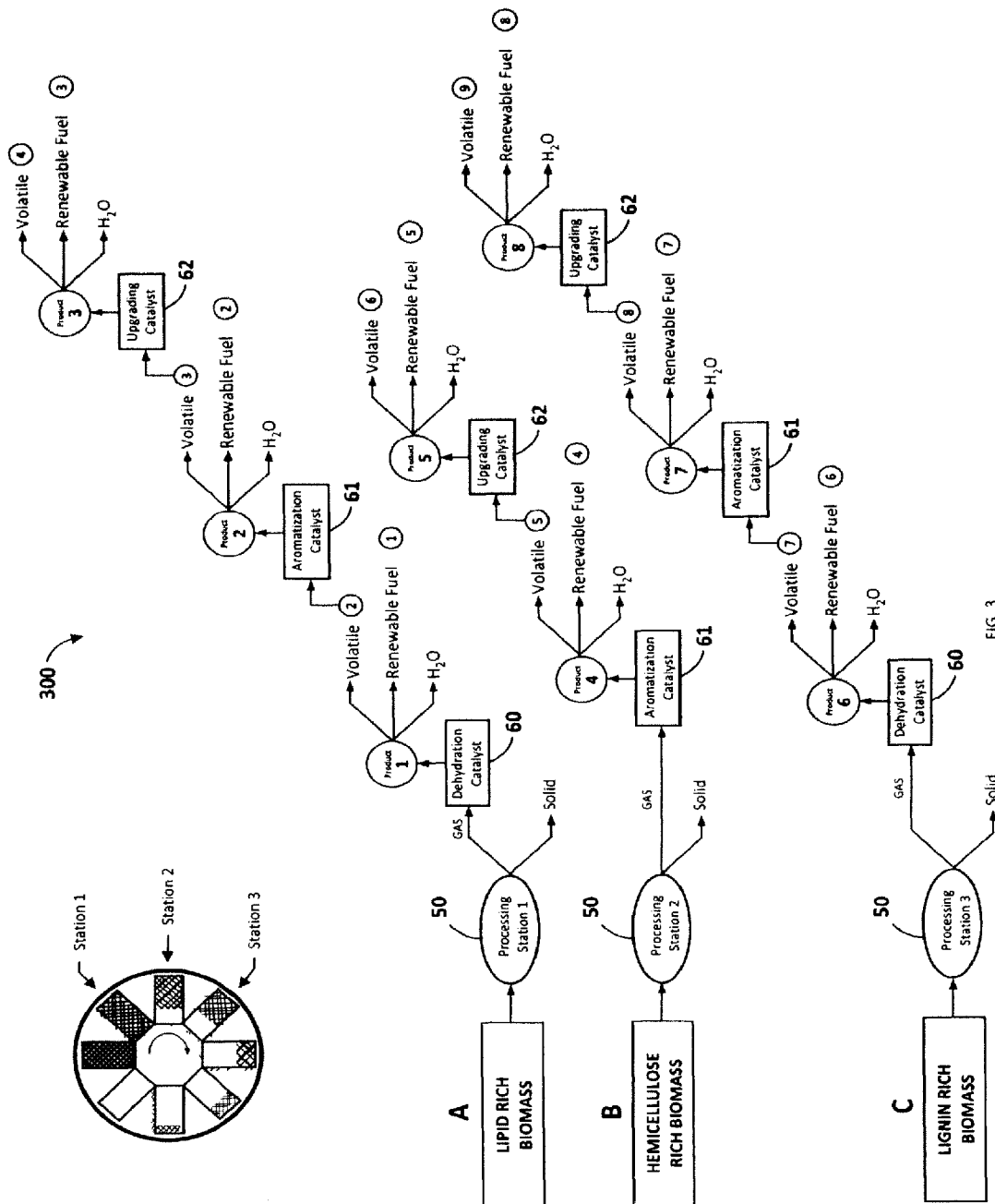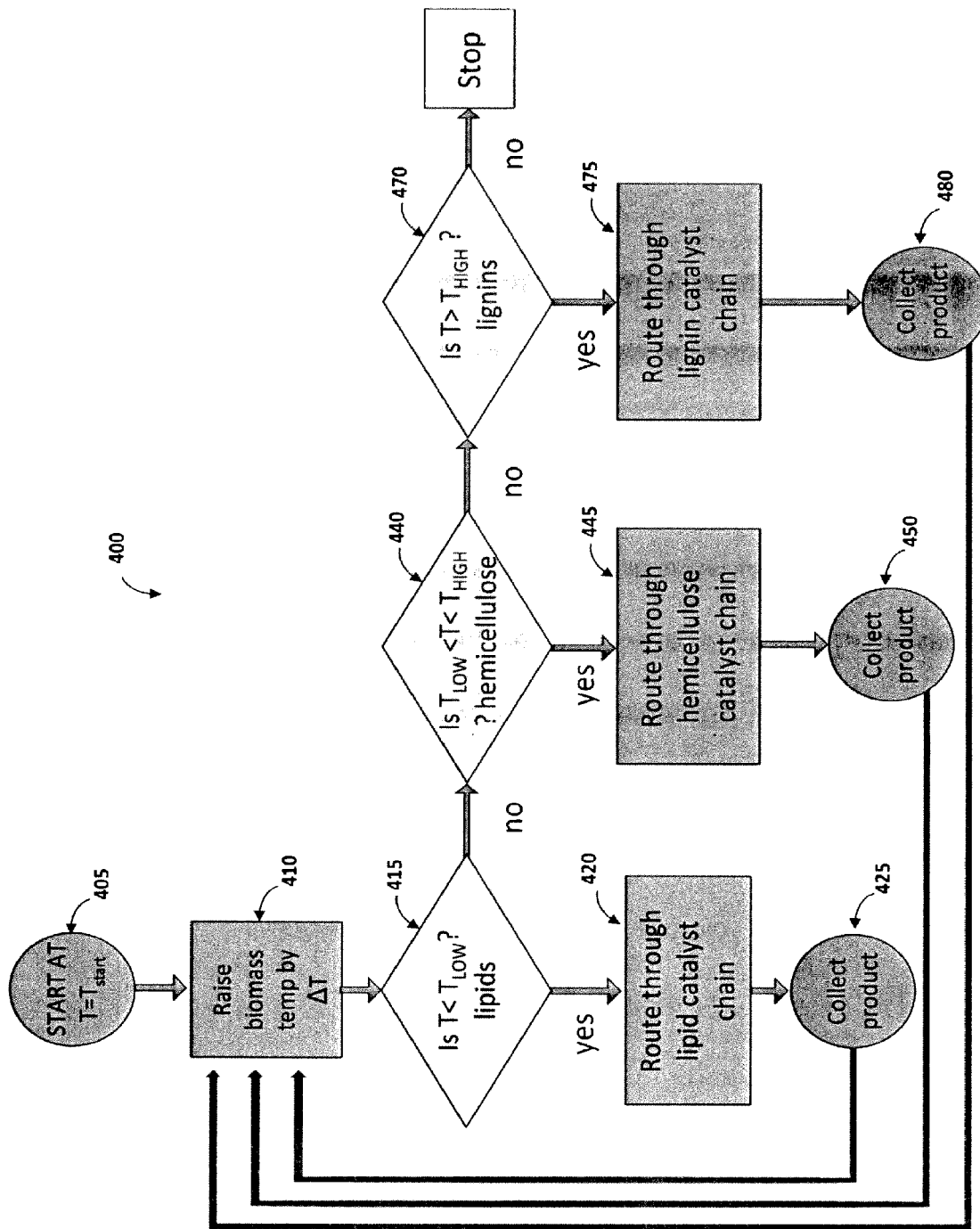
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FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6A

US Diesel #2

Bio Diesel B99

Product using Present Invention
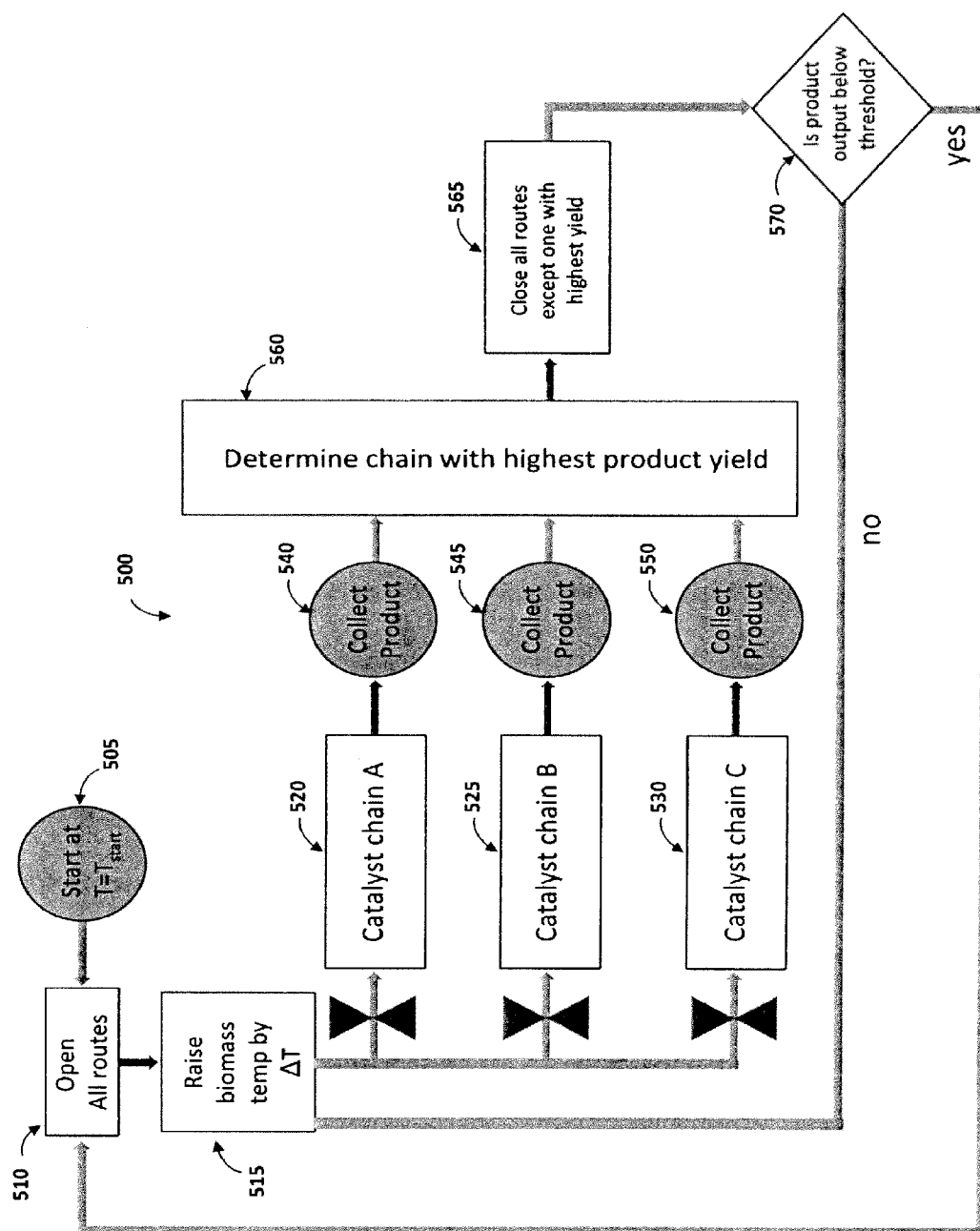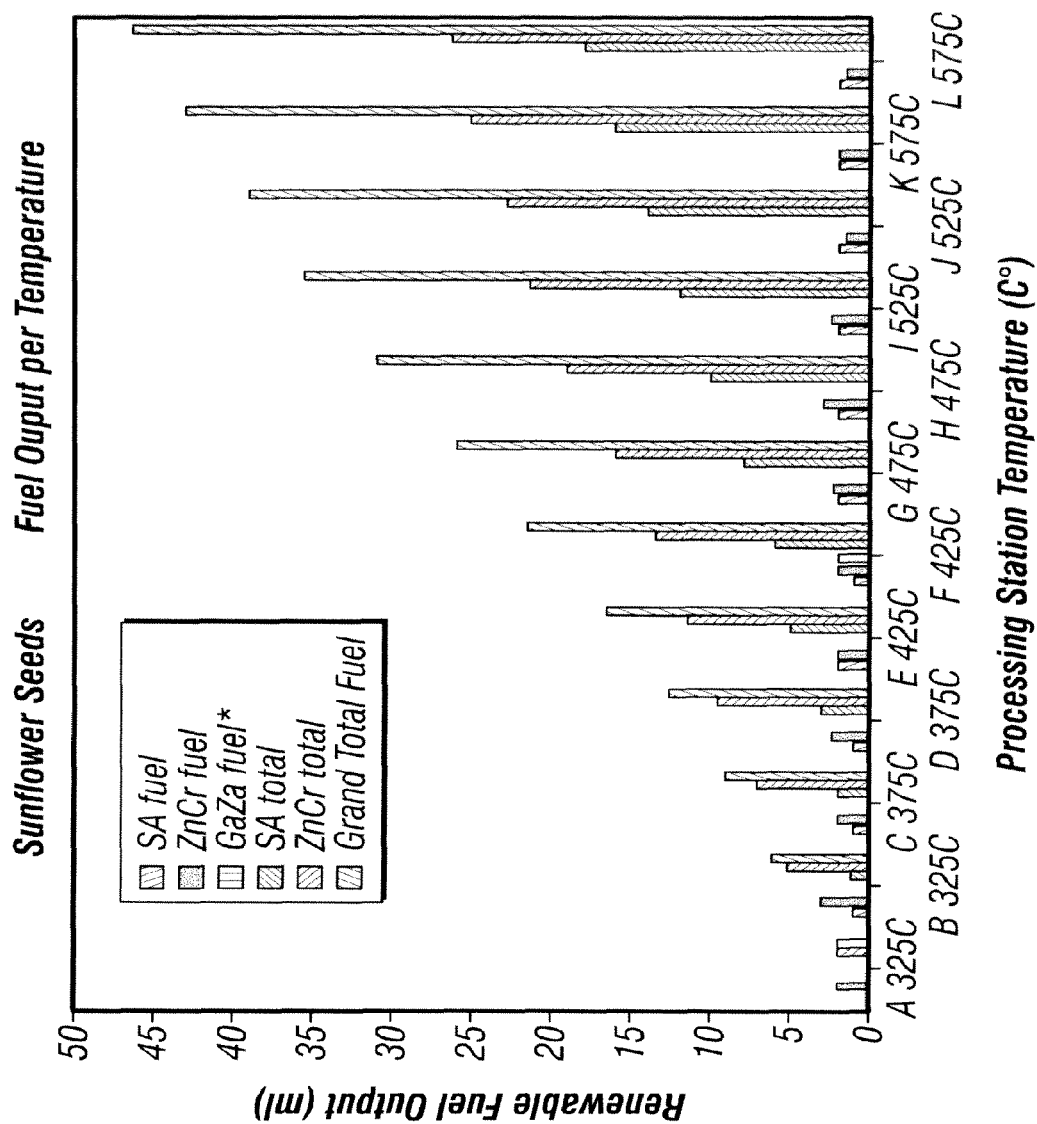
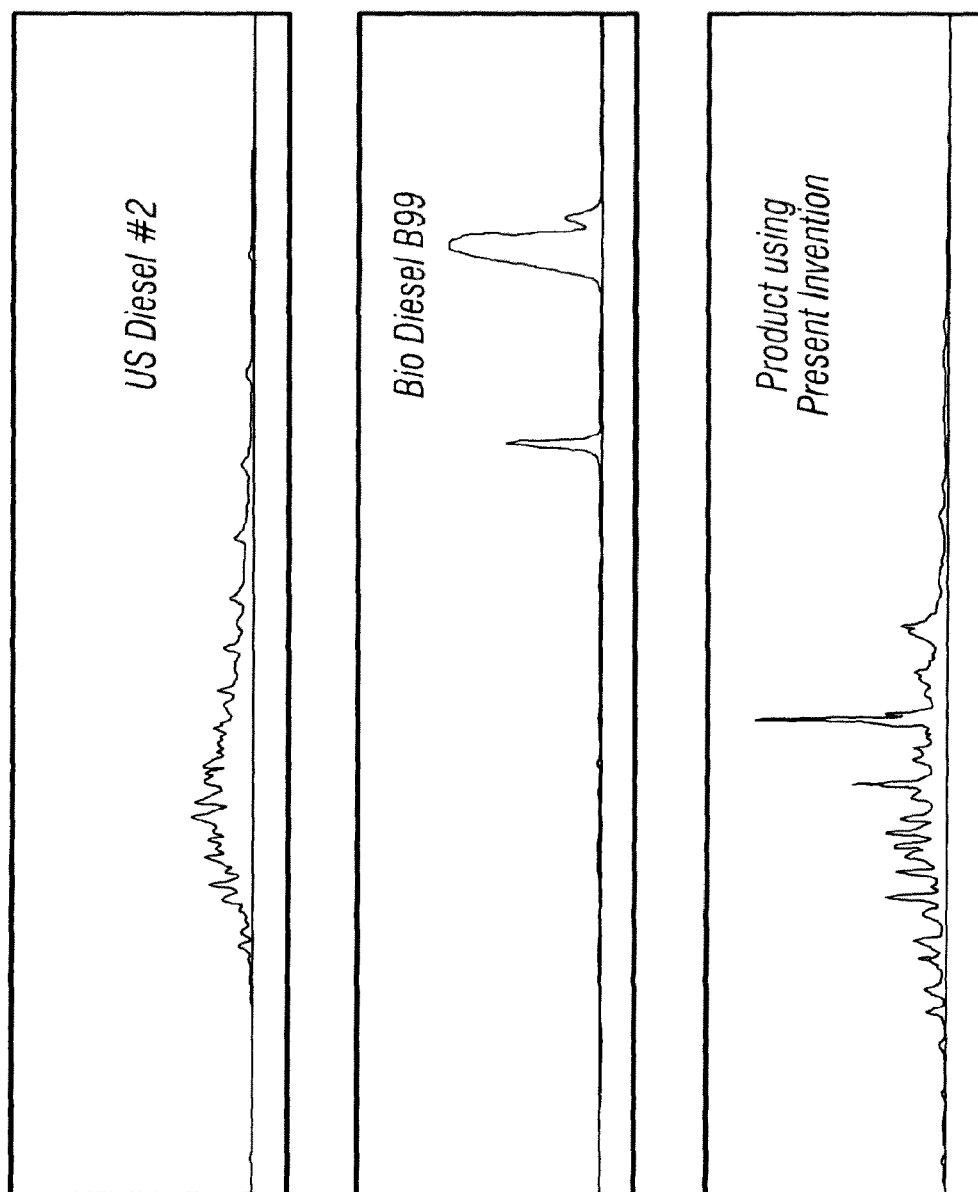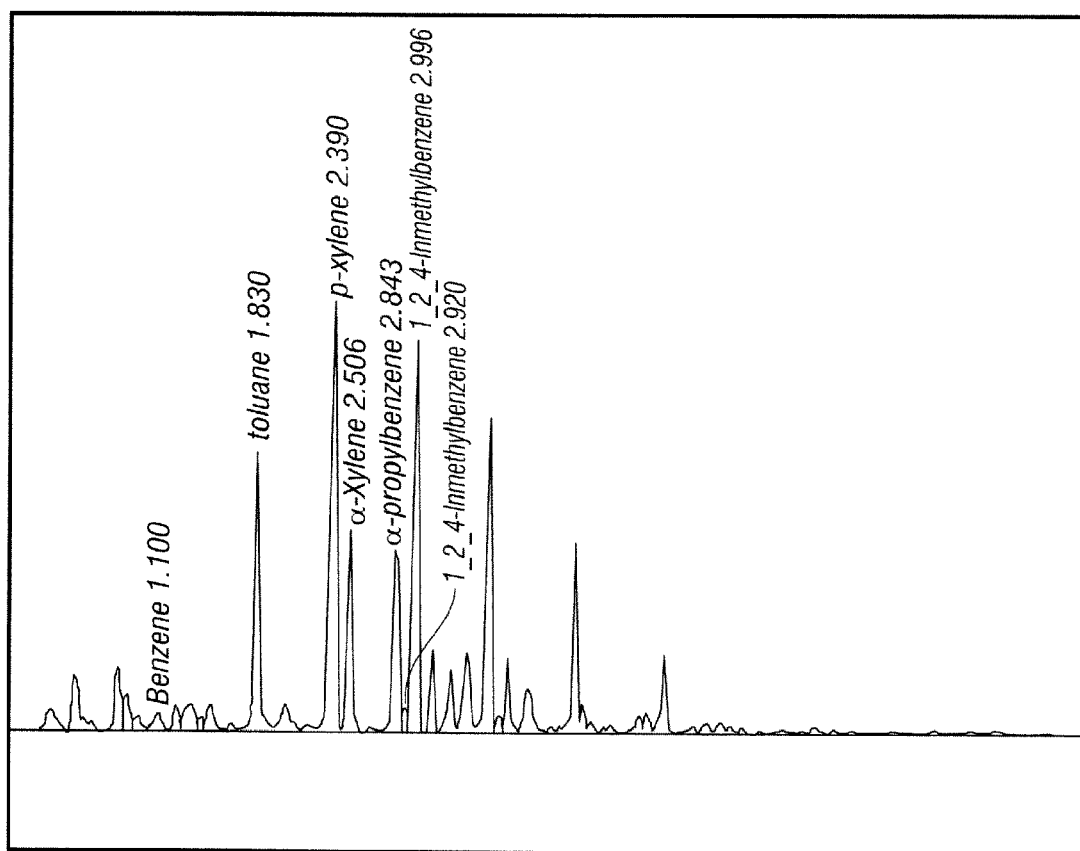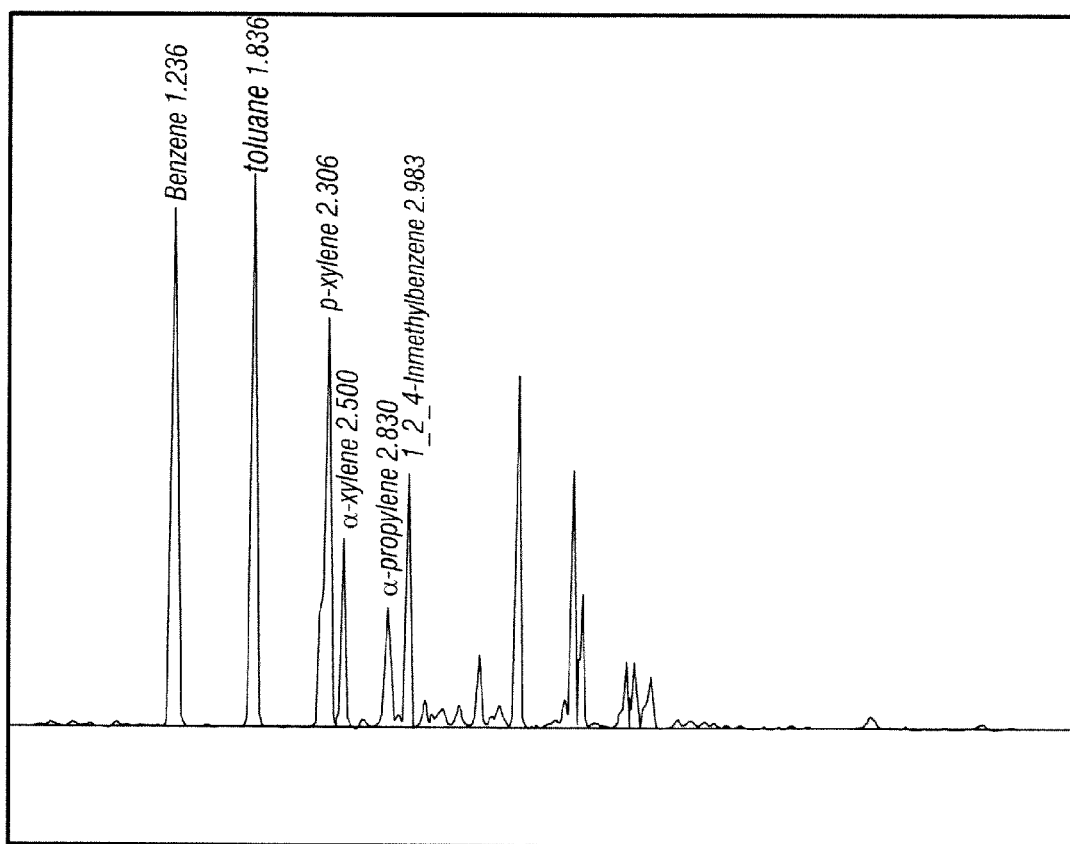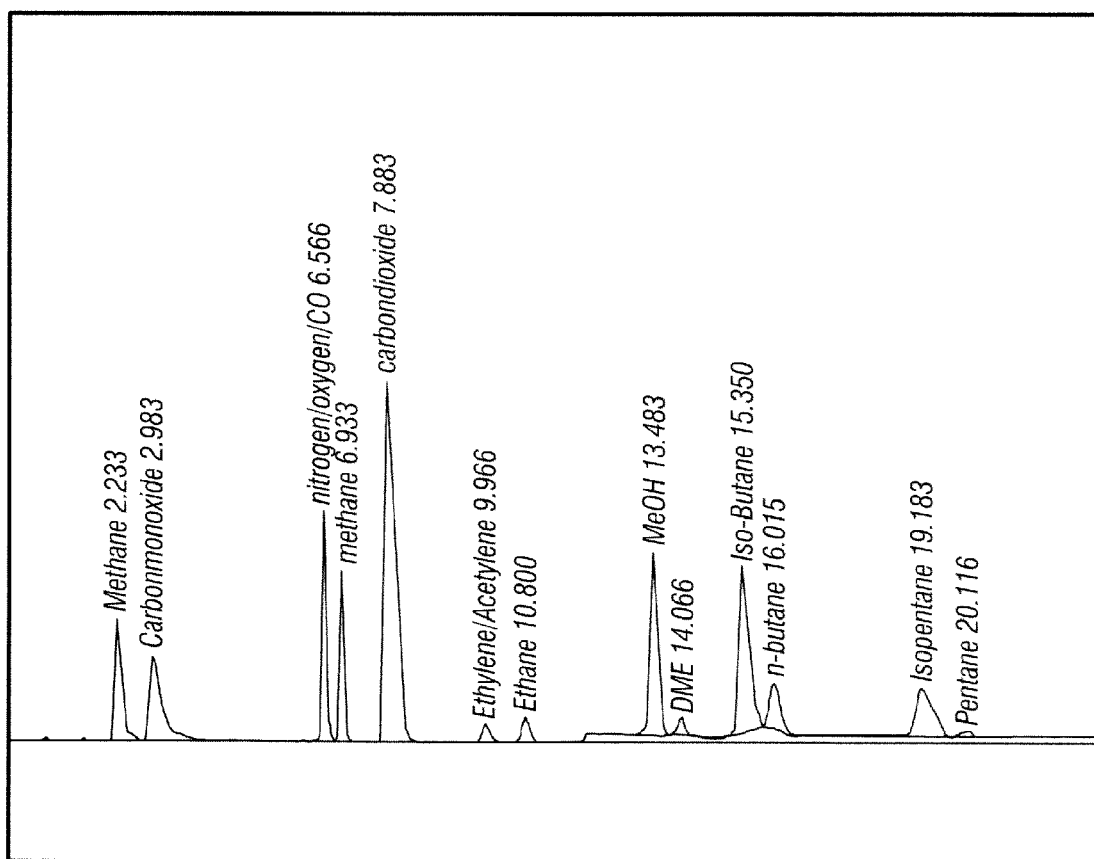**FIG. 6B**

FIG. 6C

FIG. 6D

FIG. 7

SYSTEM AND METHOD FOR MAKING RENEWABLE FUELS

REFERENCE TO RELATED APPLICATIONS

This application is a continuation of International Patent Application No. PCT/US12/22602, filed on Jan. 25, 2012, which claims priority to U.S. patent application Ser. No. 13/071,016, filed Mar. 24, 2011, now U.S. Pat. No. 8,143,464, and U.S. patent application Ser. No. 13/071,038, filed Mar. 24, 2011, now U.S. Pat. No. 8,137,628, the contents of these applications are incorporated herein by reference in their entireties.

TECHNICAL FIELD

The present invention relates generally to systems and methods for making renewable fuels, and more particularly to the thermal chemical conversion of biomass to renewable fuels and other useful chemical compounds, including gasoline and diesel, via a series of catalysts using a programmable system.

DESCRIPTION OF THE RELATED ART

As the world continues to run through its precious resources of fossil fuels, it is going to be forced to turn to other sources of energy. Present global objectives include getting energy cheaply and quickly. Through the ages, mankind has turned to biomass to furnish energy in terms of heat by burning wood and other biomass. This is inherently a very inefficient process. Combustion may be made more efficient by introducing programmability. It is similar to introducing computers to a building that needs to be heated. In order to heat the building only when the person is present, one places a sensor in the building so that the heater turns on when the sensor detects a person. This is an example of a programmable system. Similarly, a programmable system may be introduced for chemical bond breakage resulting in efficient conversion of biomass to higher value added products, wherein only the minimum number of bonds are broken and, consequently, the minimum amount of energy is spent breaking these bonds.

Bond breaking and making are essential aspects of conversion of biomass to industrially useful products such as gasoline and diesel. Various forms of laboratory and small scale commercial biomass pyrolyzers have been developed to generate useful chemical products from the controlled pyrolysis of biomaterials ranging from wood chips to sewage sludge. Although some pyrolyzers are focused simply on producing syngas, there is considerable effort in the development of milder pyrolyzing conditions, which typically results in a condensed liquid commonly called bio-oil or pyrolysis oil. Many forms of pyrolyzers have been developed at the laboratory level to produce these intermediate compounds, which are collectively referred to as bio-oil or pyrolysis oil. Configurations include simple tube furnaces where the biomass is roasted in ceramic boats, ablative pyrolyzers where wood is rubbed against a hot surface, various forms of fluidized bed pyrolyzers where biomass is mixed with hot sand, and various simpler configurations that are based on earlier coking oven designs.

The fundamental problem with the resultant pyrolysis oil is that it is made up of hundreds to thousands of compounds, which are the result of subjecting the raw biomass to a wide range of temperature, time, and pressure profiles in bulk. When this process is complicated by the thousands of major

bio-compounds in the original bio-feedstock, the result is a nearly intractable array of resultant compounds all mixed together. Pyrolysis oils from such processes are typically not thermodynamically stable. They contain active oxygenated free radicals that are catalyzed by organic acids and bases such that these oils typically evolve over a period of a few days from light colored liquids to dark mixtures with tar and resinous substances entrained in the mix. Also, attempts to re-gasify pyrolysis oil typically result in additional chemical reactions, which produce additional biochar and a shift to lower molecular weight components in the resulting gas stream. Although fairly high yields of pyrolysis oil can be achieved in laboratory scale experiments, larger industrial scale demonstration projects typically produce much lower yield. This is presumably due to the wider range of temperatures, hold times, and localized pressures within the much larger heated three dimensional volumes of such scale-up architectures.

Previous efforts to introduce a programmable adaptability to catalytic systems include Gehrer's design of building several parallel reactors, in analogy to a microprocessor bus, to study catalytic gas reactions. (Journal of Physics E: Scientific Instruments 18 (1985) 836). U.S. Pat. No. 6,548,026 by Dales et al. and U.S. Pat. No. 6,994,827 by Safir et. al. disclose programmable parallel reactors capable of controlling vessel stirring rate, temperature and pressure. Additionally, U.S. Patent Application 2010/0223839 to Garcia-Perez et al. discloses heating biomass to a first temperature aimed to enhance the subsequent anhydro sugar content developed in the oil portion of the biomass pyrolysis product. The aim is to enhance the fermentation capability of the oil portion for subsequent ethanol production. This is an example of a somewhat programmable system for biomass conversion.

BRIEF SUMMARY OF EMBODIMENTS OF THE INVENTION

Embodiments of the present invention provide a system and method for the conversion of biomass to renewable fuels. By renewable fuel is meant any combustible fuel that is derived from biomass and that is useful for transportation or other purposes, including such fuels as gasoline, diesel, jet fuel, or other useful fuel blends (such as a blend of benzene, toluene and xylene (BTX))). In one embodiment, the system comprises a device containing a programmable number of processing stations (N) and an array of catalysts; a means for subjecting biomass within these stations to programmable temperatures (Tstart); a means for incrementing individual processing station temperatures by programmable increments (ΔT) to produce a volatile and non-volatile component; a means for incrementing the non-volatile component temperature by ΔT to further produce additional volatile and non-volatile components; and a means for subjecting the volatile components generated in each station through a series of catalysts selected from the group of dehydration catalysts, aromatization catalysts, and gas-upgrading catalysts to produce at least one renewable fuel.

Some embodiments of the invention involve a system and method for creating a programmable process wherein chemical compounds from biomass decomposition are routed to distinct catalyst chains to produce products containing renewable fuels and other value added products.

Further embodiments of this invention are directed toward an efficient system for the conversion of biomass pyrolysis products.

Additional embodiments are directed toward a process for extracting the maximum amount of energy from biomass for

the conversion to gasoline or diesel that depends on the temperature of devolatilization of the biomass.

Yet another embodiment of this invention involves a process for extracting the maximum amount of energy from biomass for the conversion to gasoline or diesel that depends on load balancing a catalyst output at certain temperatures.

Other features and aspects of the invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, which illustrate, by way of example, the features in accordance with embodiments of the invention. The summary is not intended to limit the scope of the invention, which is defined solely by the claims attached hereto.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention, in accordance with one or more various embodiments, is described in detail with reference to the following figures. The drawings are provided for purposes of illustration only and merely depict typical or example embodiments of the invention. These drawings are provided to facilitate the reader's understanding of the invention and shall not be considered limiting of the breadth, scope, or applicability of the invention. It should be noted that for clarity and ease of illustration these drawings are not necessarily made to scale.

FIG. 1 is a drawing illustrating N processing stations on a race track, wherein each processing station is operating at a particular temperature.

FIG. 2 is a flow diagram illustrating a programmable catalyst chain with three stations, in accordance with the principles of the invention.

FIG. 3 is a more detailed flow diagram of the programmable catalyst chain of FIG. 2, in accordance with the principles of the invention.

FIG. 4 is a flowchart depicting an algorithm that depends on incrementing the processing station temperature until a desired maximum temperature is reached, in accordance with the principles of the invention.

FIG. 5 is a flowchart depicting an algorithm that depends on balancing output from various catalyst chains, in accordance with the principles of the invention.

FIG. 6A is a plot of fuel output versus temperature for sunflower seeds using a dehydration catalyst, aromatization catalyst and gas-upgrading catalyst; FIG. 6B shows a comparative output of the A cut (after dehydration catalyst) versus U.S. Diesel #2 and Biodiesel B99; and FIGS. 6C and 6D show gas chromatograms (GC) data for renewable fuels obtained after the aromatization catalyst and gas-upgrading catalyst.

FIG. 7 is a GC plot of volatile gases collected after the aromatization catalyst using red fir as input biomass.

The figures are not intended to be exhaustive or to limit the invention to the precise form disclosed. It should be understood that the invention can be practiced with modification and alteration, and that the invention be limited only by the claims and the equivalents thereof.

DETAILED DESCRIPTION OF THE EMBODIMENTS OF THE INVENTION

The present invention is directed toward a programmable system for routing biomass decomposition products through a system comprised of processing stations and a series of catalysts. It realizes a programmable system for maximizing output from a pyrolysis system. There are three basic approaches in this programmable system: a) routing based on knowledge of the initial composition of the biomass, b) routing based on knowledge of the temperature of biomass devolatilization, and c) routing based on load balancing. The full nature of these approaches will now be described by reference to the figures.

Methods of introducing biomass into a processing station include introduction via conveyor belts, hoppers, and/or pulverizers. The pyrolyzer described herein may include these components enveloped in one system, where, for example, the pulverization and pyrolysis components are intimately connected. Biomass may be introduced in raw form or dry form, or may be dried within the pyrolysis chamber when the pyrolysis starts.

As used herein, the term 'biomass' includes any material derived or readily obtained from plant sources. Such material can include without limitation: (i) plant products such as bark, leaves, tree branches, tree stumps, hardwood chips, softwood chips, grape pumice, sugarcane bagasse, switchgrass; and (ii) pellet material such as grass, wood and hay pellets, crop products such as corn, wheat and kenaf. This term may also include seeds such as vegetable seeds, fruit seeds, and legume seeds.

The term 'biomass' can also include: (i) waste products including animal manure such as poultry derived waste; (ii) commercial or recycled material including plastic, paper, paper pulp, cardboard, sawdust, timber residue, wood shavings and cloth; (iii) municipal waste including sewage waste; (iv) agricultural waste such as coconut shells, pecan shells, almond shells, coffee grounds; and (v) agricultural feed products such as rice straw, wheat straw, rice hulls, corn stover, corn straw, and corn cobs.

Referring to FIG. 1, a series of N processing stations 50 are arranged around a rectangular track 52 sequentially. A processing station 50 may comprise any of a number of well-known pyrolysis reactors, including fixed bed reactors, fluidized bed reactors, circulating bed reactors, bubbling fluid bed reactors, vacuum moving bed reactors, entrained flow reactors, cyclonic or vortex reactors, rotating cone reactors, auger reactors, ablative reactors, microwave or plasma assisted pyrolysis reactors, and vacuum moving bed reactors. It may also comprise a chamber in a biomass fractionating system as described in co-owned U.S. Patent Publication No. 2010/0180805, the content of which is incorporated herein by reference in its entirety.

At any one time, each processing station 50 is operated at a certain temperature (marked next to each processing station in FIG. 1 as $T_1 \ldots T_N$). Thus, the Nth station is operated at temperature T_N. The first processing station is Station 1. Each processing station 50 can be dialed to any temperature that is equal to or higher than the previous processing station. The starting processing station temperature is typically determined by the initial composition of the biomass. The device accommodates a total of N processing stations, where N is operator adjustable from 2 to 1000, preferably between 2 and 100, and most preferably between 2 and 50. A station temperature can be incremented by a variable increment ΔT, which can be in the range of 0° C. to 200° C. In one embodiment, all processing stations 50 operate at the same temperature. In another embodiment, each subsequent processing station temperature is incrementally higher by ΔT from the previous processing station. In still another embodiment, a group of adjacent processing stations are operated at the same temperature T, followed by another group of adjacent processing stations which are operated at temperature $T+x*\Delta T$, followed still by another group of processing stations operating at temperature $T+y*\Delta T$, where x and y are any numbers greater or equal to 1.

The processing stations **50** produce volatile and non-volatile components when heated. Because the material can be heated within a relatively narrow temperature range, the non-volatile component (in the form of partially formed char) has additional volatile components embedded therein, which are extractable and processed in subsequent processing stations. The output of these processing stations is connected to an array of catalysts as described below.

Biomass is typically comprised of a wide array of compounds classified within the categories of cellulose, hemicelluloses, lignin, starches, and lipids. These compounds go through multiple steps of decomposition when subject to the pyrolysis process. For example, hemicelluloses comprise C5 sugars such as fructose and xylose, which yield furfural and hydroxymethylfurfurals upon thermolysis. The latter compounds can be further converted to fuel intermediates furan and tetrahydrofuran. The relatively narrow temperature windows experienced within a processing station **50** allows for the collection of these useful intermediates.

FIG. **2** depicts an embodiment of the present invention having eight processing stations **50** and a series of catalyst channels comprising a dehydration catalyst **60**, an aromatization catalyst **61** and a gas-upgrading catalyst **62**. The output from each catalytic array when cooled is comprised of volatile gases, renewable fuel and water. The volatile gases are then programmed to pass through subsequent catalytic columns. Depending on the temperature of the processing station **50** and the biomass composition, the volatile components from any given processing station can be channeled through one or more catalysts **60**, **61**, **62** using selector switches **55**, **56**, **57**. Line **21** shows that an optional co-solvent may be added as an additional input to the aromatization catalyst **61**. The co-solvent may be generated from a typical syngas converter **64**. Carbon monoxide and hydrogen for the syngas converter (to generate the co-solvent) may be obtained via well-known reactions with the left-over carbonaceous solid in a processing station **50**. The co-solvent may comprise oxygenates such as aldehydes, alcohols, ketones, ethers, and carboxylates, as well as hydrocarbons.

If the volatile components from the processing station **50** are selected to go through a dehydration catalyst **60**, then the output is passed through a room temperature separator **32**, which separates the output into water, renewable fuel **33**, and volatile gases **34**. The volatile gases are then routed through the aromatization catalyst **61** to produce a product that upon cooling with cold separator **35** gives water, renewable fuel **36** and volatile gases **37**, which may include combustible gases **41**. These combustible gases can then be released via a variable release valve **58**. The variable release valve can control the routing of the volatile gases **37** to either a gas-upgrading catalyst chamber, or a combustible gas treatment plant, or both. Upon cooling via cold separator **38**, the product from the gas-upgrading catalyst **62** produces water, renewable fuel **39** and volatile gases **40**, which may include combustible gas mixture **42**. This combustible gas mixture can be either treated in a combustible gas treatment plant or recycled via a recirculation pump **59** to the aromatization catalyst chamber. In another embodiment, the combustible gas mixture **42** may be recycled to one or more of the following: (a) at least one or more of the processing stations **50**, (b) the dehydration catalyst **60**, (c) the aromatization catalyst **61**, and the (d) gas-upgrading catalyst **62**.

FIG. **3** shows an embodiment **300** of the present invention using knowledge of the initial composition of the biomass for converting various types of biomass feedstocks with three processing stations **50** and an array of catalytic columns for optimal product yield. The biomass feedstocks in various

stations can come from a single biomass input which are subsequently processed using the three stations, or from multiple independent biomass inputs. While the number of processing stations can vary, the same catalytic columns are used to convert the volatile gases to renewable fuels. The order in which the catalytic columns are selected can vary.

Station 1 when fed with a lipid rich biomass (A) produces a product comprising a volatile gas and a carbonaceous solid. Station 1 preferably operates at less than 300° C. The volatile components are passed through a dehydration catalyst **60** to produce a first product. This first product is cooled using a room temperature trap and is comprised of water, a first renewable fuel and a second volatile component. The first renewable fuel is then recovered. The dehydration catalyst operates at less than 2 bar pressure, preferably in the temperature range of 400-700° C., most preferably in the range of 400° C. to 500° C.

The dehydration catalyst **60** can be any acid catalyst. Suitable acid catalysts for the present invention are heterogeneous (or solid) acid catalysts. The at least one solid acid catalyst may be supported on at least one catalyst support (herein referred to as a supported acid catalyst). Solid acid catalysts include, but are not limited to, (1) heterogeneous heteropolyacids (HPAs) and their salts, (2) natural clay minerals, such as those containing alumina or silica (including zeolites), (3) cation exchange resins, (4) metal oxides, (5) mixed metal oxides, (6) inorganic acids or metal salts derived from these acids such as metal sulfides, metal sulfates, metal sulfonates, metal nitrates, metal phosphates, metal phosphonates, metal molybdates, metal tungstates, metal borates, and (7) combinations of groups 1 to 6.

Suitable HPAs include compounds of the general Formula $X_a M_b O_c^{q-}$, where X is a heteroatom such as phosphorus, silicon, boron, aluminum, germanium, titanium, zirconium, cerium, cobalt or chromium, M is at least one transition metal such as tungsten, molybdenum, niobium, vanadium, or tantalum, and q, a, b, and c are individually selected whole numbers or fractions thereof. Methods for preparing HPAs are well known in the art. Natural clay minerals are well known in the art and include, without limitation, kaolinite, bentonite, attapulgite, montmorillonite and zeolites. Suitable cation exchange resins are styrene-divinylbenzene copolymer-based strong cation exchange resins such as Amberlyst® (Rohm & Haas; Philadelphia, Pa.), Dowex® example, Dowex® Monosphere M-31) (Dow; Midland, Mich.), CG resins from Resintech. Inc. (West Berlin, N.J.), and Lewatit resins such as MonoPlus™ S 100 H from Sybron Chemicals Inc. (Birmingham, N.J.). When present, the metal components of groups 4 to 6 may be selected from elements from Groups I, IIa, IIIa, VIIa, VIIIa, Ib and IIb of the Periodic Table of the Elements, as well as aluminum, chromium, tin, titanium and zirconium. Fluorinated sulfonic acid polymers can also be used as solid acid catalysts for the process of the present invention.

The second volatile component is then routed to an aromatization catalyst **61** to produce a second product. This second product in turn is cooled using a cold trap at 0-20° C., more preferably at 0-5° C. The output from the cold trap is comprised of water, a second renewable fuel and a third volatile component. The second renewable fuel is then recovered. The aromatization catalyst **61** is operated at less than 2 bar pressure, preferably in the temperature range of 300° C. to 500° C., most preferably in the range of 325° C. to 400° C. The aromatization catalyst **61** can be comprised of MFI type zeolites and metal modified MFI type zeolites, where the metal is selected from the group consisting of: Group VIB metals,

Group VIIB metals, Group VIII metals, Group IB metals, Group IIB metals, Ga, in, and all combinations thereof.

The third volatile component is then routed to a gas-upgrading catalyst **62** to produce a third product. This third product in turn is cooled using a cold trap at 0-20° C., more preferably at 0-5° C. The output from the cold trap is comprised of water, a third renewable fuel and a fourth volatile component. The third renewable fuel is then recovered. The gas-upgrading catalyst **62** is operated at less than 2 bar pressure and preferably in the temperature range of 400° C. to 700° C., most preferably in the range of 500° C. to 600° C. The gas-upgrading catalyst **62** can be comprised of metal modified MFI type zeolites, where the metal is selected from the group consisting of: Ga, Zn, In, Mo, W, Cr, Pt, Pd, Rh, Ru, Au, Ir, and combinations thereof. The fourth volatile component can be recirculated to at least one of the following: a) one or more processing stations **50**, b) the dehydration catalyst **60**, c) the aromatization catalyst **61**, d) the gas-upgrading catalyst **62**, and e) a combustible gas treatment plant.

Referring still to FIG. **3**, Station 2 can comprise a hemicellulose rich biomass (B) derived from another biomass feedstock or a carbonaceous solid from a previous station **50** that contains volatile components that did not volatilize in the prior station. Station 2 preferably operates at greater than 300° C. and less than 500° C. The temperature in Station 2 can be programmably incremented (ΔT) by the operator. The temperature increment can preferably be in the range of 10-200° C. Station 2 produces a product which is comprised of a volatile component and a carbonaceous solid that is different than the carbonaceous solid produced in the previous station. The volatile component produced in Station 2 is then routed through the aromatization catalyst **61** to produce a fourth product. This fourth product is then cooled using a cold trap at 0-20° C., most preferably at 0-5° C. The fourth renewable fuel is then recovered. The output from the cold trap is comprised of water, a fourth renewable fuel and a fifth volatile component. The aromatization catalyst **61** is operated at less than 2 bar pressure and preferably in the temperature range of 300° C. to 500° C., most preferably in the range of 325° C. to 400° C.

The fifth volatile component is then routed to the gas-upgrading catalyst **62** to produce a fifth product. This fifth product in turn is cooled using a cold trap at 0-20° C., most preferably at 0-5° C. The output from the cold trap is comprised of water, a fifth renewable fuel and a sixth volatile component. The fifth renewable fuel is then recovered. The gas-upgrading catalyst **62** is operated at less than 2 bar pressure and preferably in the temperature range of 400° C. to 700° C., most preferably in the range of 500° C. to 600° C. The sixth volatile component can be recirculated to at least one of the following: a) one or more processing stations **50**, b) the dehydration catalyst **60**, c) the aromatization catalyst **61**, d) the gas-upgrading catalyst **62**, and e) a combustible gas treatment plant.

Still referring to FIG. **3**, Station 3 operates at greater than 500° C. processing either an independent lignin-rich biomass feedstock or the leftover carbonaceous solid from the previous station. Station 3 produces a product which contains volatile gases and a different carbonaceous solid. These volatile components are passed through a dehydration catalyst **60** to produce a sixth product. This sixth product is cooled using a room temperature trap and is comprised of water, a sixth renewable fuel and a seventh volatile component. The sixth renewable fuel is then recovered. The dehydration catalyst **60** operates at less than 2 bar pressure and preferably in the

temperature range of 400-700° C., most preferably in the range of 400° C. to 500° C. The dehydration catalyst **60** can be the same as described above.

The seventh volatile component is then routed to the previously described aromatization catalyst **61** to produce a seventh product. This seventh product in turn is cooled using a cold trap at 0-20° C., most preferably at 0-5° C. The output from the cold trap is comprised of water, a seventh renewable fuel and an eighth volatile component. The seventh renewable fuel is then recovered. The aromatization catalyst **61** is operated at less than 2 bar pressure and preferably in the temperature range of 300° C. to 500° C., most preferably in the range of 325° C. to 400° C.

The eighth volatile component is then routed to the previously described gas upgrading catalyst **62** to produce an eighth product. This eighth product in turn is cooled using a cold trap at 0-20° C., most preferably at 0-5° C. The output from the cold trap is comprised of water, an eighth renewable fuel and a ninth volatile component. The eighth renewable fuel is then recovered. The gas-upgrading catalyst **62** is operated at less than 2 bar pressure and preferably in the temperature range of 400° C. to 700° C., most preferably in the range of 500° C. to 600° C. The ninth volatile component can be recirculated to at least one of the following: a) one or more processing stations **50**, b) the dehydration catalyst **60**, c) the aromatization catalyst **61**, d) the gas-upgrading catalyst **62**, and e) a combustible gas treatment plant.

The embodiment of FIG. **3** involves an approach that exploits knowing the initial composition of the biomass input, and then adjusting the routing of the decomposition products based on this initial composition. Accordingly, given a hemicellulose rich feedstock, it may be beneficial to set all of the processing stations **50** to a temperature greater than 300° C. Similarly, given a lignin-rich feedstock, it may be beneficial to operate all the processing stations **50** at temperatures greater than 500° C. Such an operation is expected to utilize all the stations in the most efficient manner for maximizing fuel output.

Another approach entails the use of an algorithm that raises an individual processing station temperature by ΔT until a desired end temperature is reached. This approach is illustrated in FIG. **4**, which shows a temperature algorithm flowchart **400** for a single processing station. For three cuts derived from lipids, hemicellulose and lignins, one would select T_{LOW} around 300° C., and T_{HIGH} around 500° C.

Referring to FIG. **4**, T=T_{start} at operation **405**. Operation **410** involves raising the biomass temperature by ΔT. Next, operation **415** involves determining whether T<T_{LOW} for the lipids. If so, the next steps entail routing the biomass through the lipid catalyst chain (operation **420**), collecting the product (operation **425**), and proceeding to raise the biomass temperature by ΔT (operation **410**). If operation **415** is false, operation **440** involves determining whether T_{LOW}<T<T_{HIGH} for the hemicellulose. If so, the next steps include routing the biomass through the hemicellulose catalyst chain (operation **445**), collecting the product (operation **450**), and proceeding to raise the biomass temperature by ΔT (operation **410**). If operation **440** is false, operation **470** involves determining whether T>T_{HIGH} for the lignins. It so, the next steps entail routing the biomass through the lignin catalyst chain (operation **475**), collecting the product (operation **480**), and proceeding to raise the biomass temperature by ΔT (operation **410**). The algorithm ends if operation **470** is false.

Yet another approach involves load balancing the output from each catalytic chain in order to maximize product yield. This approach is illustrated in FIG. **5**, which depicts a load balancing algorithm flowchart **500** for one processing n.

According to this approach, knowledge of composition not required. Rather, the optimal catalytic route is determined by comparing product output yield from each route. Subsequently, the temperature is incremented until a final desired temperature is achieved.

Referring to FIG. 5, $T=T_{start}$ at operation **505**. Operation **510** involves opening all routes. Next, operation **515** comprises raising the biomass temperature by ΔT. At this point, this approach splits into three routes, specifically catalyst chain A (operation **520**), catalyst chain B (operation **525**), and catalyst chain C (operation **530**). Product is collected for each catalyst chain in subsequent operations **540**, **545**, **550**. Operation **560** entails determining the optimal catalytic route is calculated by comparing product output yield from each route and determining the catalyst chain having the highest product yield. Then, operation **565** comprises closing all routes except the one with the highest yield. Operation **570** involves determining whether the product output is below a threshold level. If so, the algorithm proceeds to open all routes (operation **510**). If not, the algorithm proceeds to raise the biomass temperature by ΔT (operation **515**).

Illustrative Example 1

Referring now to FIG. **6A**, this illustrative example is the equivalent to six processing stations **50** operating at six different temperatures wherein the input biomass is fed at 325° C. and the final carbonaceous solid is removed at 575° C. 150 g of biomass consisting of commercial sunflower seeds along with dimethyl ether as co-solvent were devolatilized starting at a temperature of 325° C. and ending at 575° C. with a temperature increment of 50° C. for every hour. 131 g of methanol was passed through a silica alumina catalyst to generate the required co-solvent. The output was passed through three different catalyst columns in series including a dehydration catalyst **60**, an aromatization catalyst **61**, and a gas-upgrading catalyst **62** as illustrated in FIG. **3** for cut A. More particularly, this experiment employed a silica alumina dehydration catalyst, a Zn and Cr modified ZSM-5 aromatization catalyst, and a Ga modified ZSM-5 gas-upgrading catalyst. FIG. **6A** is a chart showing the fuel collected at each temperature for each catalyst at half-hour intervals. A grand total of 46.5 ml of renewable fuel is produced by the three catalysts by the end of the run, including: (i) a total of 26.5 ml of renewable fuel collected from the aromatization catalyst **61**, (ii) a total of 18 ml of renewable fuel collected from the dehydration catalyst **60**, and (iii) a total of 2 ml of renewable fuel collected from the gas-upgrading catalyst **62**.

FIG. **6B** is a chart showing the gas chromatogram profile of the renewable fuel collected from the dehydration catalyst **60** along with comparative charts of regular US Diesel #2 fuel and Bio Diesel B99 obtained from a commercial source. The renewable fuel produced from the dehydration catalyst according to the present invention is significantly different when compared to the Biodiesel B99 and more resembles the profile of the regular US Diesel #2. Gas chromatograms shown in FIGS. **6C** and **6D** represent renewable fuel composition from the aromatization catalyst **61** and the gas-upgrading catalyst **62**, respectively. Significant amount of aromatic hydrocarbons are present in both renewable fuels.

Illustrative Example 2

This illustrative example is the equivalent to six processing stations operating at six different temperatures wherein the input biomass is again fed at 325° C. and the final carbonaceous solid is removed at 525° C. 76 g of biomass consisting

of commercial corn cobs along with 100 g of methanol were devolatilized starting at a temperature of 325° C. and ending at 525° C. with a temperature increment of 50° C. for every hour. This example assumes that corn cobs contain significant amounts of hemicellulose (C5 sugars), which may decompose in the presence of a dehydration catalyst **60**, leading to more breakage of chemical bonds than necessary. Therefore, the output was passed through two different catalyst columns in series, one consisting of an aromatization catalyst **61**, followed by a gas-upgrading catalyst **62** as illustrated in FIG. **3** for cut B. In this example, ZSM-5 was employed as the aromatization catalyst, and Ga modified ZSM-5 was employed as the gas-upgrading catalyst. A total of 29 ml of renewable fuel was collected by the end of the run from the aromatization catalyst, while a total of 5.5 ml of renewable fuel was collected from the gas-upgrading catalyst, Further analysis of the two renewable fuels collected indicated significant presence of aromatic compounds similar in composition as shown in Illustrative Example 1.

Illustrative Example 3

This illustrative example is the equivalent to six processing stations operating at six different temperatures wherein the input biomass is again fed at 325° C. and the final carbonaceous solid is removed at 575° C. 100 g of biomass consisting of red fir wood along with 131 g of methanol were devolatilized starting at a temperature of 325° C. and ending at 575° C. with a temperature increment of 50° C. for every hour. This example assumes that red fir contains significant amounts of lignins which are needed to be decomposed for efficient biomass conversion. The output was passed through two different catalyst columns in series, beginning with the dehydration catalyst **60**, and followed by an aromatization catalyst **61**. This experiment utilized silica alumina as the dehydration catalyst, and Zn and Cr modified ZSM-5 as the aromatization catalyst. A total of 30.5 ml of renewable fuel was collected by the end of the run from the aromatization catalyst **61**, whereas a total of 1 ml of renewable fuel was collected from the dehydration catalyst **60**. While the fuel from the silica alumina catalyst was diesel-like, the fuel from the aromatization catalyst had significant amounts of aromatic hydrocarbons. The volatile gases after the aromatization catalyst **61** had significant amounts of C1-C5 non-condensable hydrocarbons, as shown in FIG. **7**.

Although the invention is described above in terms of various exemplary embodiments and implementations, it should be understood that the various features, aspects and functionality described in one or more of the individual embodiments are not limited in their applicability to the particular embodiment with which they are described, but instead can be applied, alone or in various combinations, to one or more of the other embodiments of the invention, whether or not such embodiments are described and whether or not such features are presented as being a part of a described embodiment. Thus, the breadth and scope of the present invention should not be limited by any of the above-described exemplary embodiments.

Terms and phrases used in this document, and variations thereof, unless otherwise expressly stated, should be construed as open ended as opposed to limiting. As examples of the foregoing: the term "including" should be read as meaning "including, without limitation" or the like; the term "example" is used to provide exemplary instances of the item in discussion, not an exhaustive or limiting list thereof; the terms "a" or "an" should be read as meaning "at least one." "one or more" or the like; and adjectives such as "conven-

tional," "traditional," "normal," "standard," "known" and terms of similar meaning should not be construed as limiting the item described to a given time period or to an item available as of a given time, but instead should be read to encompass conventional, traditional, normal, or standard technologies that may be available or known now or at any time in the future. Likewise, where this document refers to technologies that would be apparent or known to one of ordinary skill in the art, such technologies encompass those apparent or known to the skilled artisan now or at any time in the future.

The presence of broadening words and phrases such as "one or more," "at least," "but not limited to" or other like phrases in some instances shall not be read to mean that the narrower case is intended or required in instances where such broadening phrases may be absent. Additionally, the various embodiments set forth herein are described in terms of exemplary block diagrams, flow charts and other illustrations. As will become apparent to one of ordinary skill in the art after reading this document, the illustrated embodiments and their various alternatives can be implemented without confinement to the illustrated examples. These illustrations and their accompanying description should not be construed as mandating a particular architecture or configuration.

The invention claimed is:

1. A method for converting biomass to renewable fuels, comprising:

provideing a system containing a number of processing stations (N) in communication with a series of catalysts;

heating a biomass within the stations at a starting temperature (Tstart) to produce a volatile and a non-volatile component, said biomass and said heating selected to provide volatile components suitable for producing at least one renewable fuel; and

subjecting the volatile components generated in at least one station through the series of catalysts to produce at least one renewable fuel.

2. The method of claim 1, wherein said series of catalysts is selected based on said starting temperature.

3. The method of claim 1, wherein said series of catalyst is based on the biomass composition.

4. The method of claim 3, wherein the biomass is a lipid-rich biomass and the volatile components from the lipid-rich biomass is contacted with a dehydration catalyst to produce a product which on cooling to a temperature range of 1-20° C. produces a second volatile component, a first renewable fuel and water.

5. The method of claim 3, wherein the biomass is a hemicellulose-rich biomass and a volatile components from the hemicellulose-rich biomass is contacted directly with an aromatization catalyst to produce a product which on cooling to a temperature of 0-5° C. produces a second volatile component, a first renewable fuel and water.

6. The method of claim 3, wherein the biomass is a lignin-rich biomass and the volatile component from the lignin-rich biomass is contacted with a dehydration catalyst to produce a product which on cooling to 2-20° C. produces a second volatile component, a renewable fuel and water.

7. The method of claim 1, further comprising incrementing an individual processing station temperature by increments (ΔT) to produce a volatile and a non-volatile component, said biomass and said incremental heating selected to provide incremental volatile components suitable for producing at least one renewable fuel.

8. The method of claim 7, wherein the increment is in the range of 0° C. to 200° C.

9. A method for converting biomass, comprising:

providing a device containing a number of processing stations (N) and a series of catalysts;

subjecting biomass within the stations to at least one starting temperature (Tstart); and

incrementing an individual processing station temperature by increments (ΔT) to produce a volatile and a non-volatile component.

10. The method of claim 9, further comprising subjecting the volatile components generated in each station through a sequence of catalysts to produce at least one-renewable fuel.

11. The method of claim 9, further comprising:

identifying the temperature of an individual processing station after a temperature increment;

routing the volatile components generated at the individual processing station through a series of catalysts, said series of catalysts determined by the incremented temperature.

12. The method of claim 10, wherein the sequence of catalyst contact is determined by renewable fuel yield or by temperature of devolatization of biomass components.

13. The method of claim 1 or 9, wherein a co-solvent is added to volatile components or added to at least one of the processing stations, and the co-solvent comprises at least one co-solvent selected from the group consisting of alcohols, aldehydes, ketones, ethers, carboxylic acids, and hydrocarbons, and wherein the co-solvent is generated via a syngas conversion catalyst.

14. The method of claim 1 or 9, wherein biomass is selected from the group consisting of lipids, hemicellulose, cellulose and lignins.

15. A system for the conversion of biomass to combustible fuels, comprising: a device containing a number of processing stations (N) and a series of catalysts;

a heater for subjecting biomass within the stations to at least one starting temperature (Tstart);

a controller for incrementing an individual processing station temperature by increments (ΔT) to produce a volatile and a non-volatile component;

series of catalysts for contacting the volatile components generated in each station to produce at least one renewable fuel; and

a processor for receiving data related to one or more of renewable fuel yield or temperature of devolatization of biomass components and determining a sequence of catalyst contacts.

16. A system for converting biomass to a renewable fuel, comprising:

a device containing a number of processing stations (N) and a series of catalysts selected from the group consisting of catalytic dehydration, catalytic aromatization and catalytic gas-upgrading;

means for subjecting biomass within the stations to at least one starting temperature (Tstart);

means for incrementing an individual processing station temperature by increments (ΔT) to produce a volatile and a non-volatile component; and

means for subjecting the volatile components generated in each station through the series of catalysts to produce at least one renewable fuel.

17. The system of claim 15, wherein the series of catalysts are selected from the group consisting of catalytic dehydration, catalytic aromatization and catalytic gas-upgrading.

18. The system of claim 15 or 16, wherein N ranges from 2 to 1000, and wherein Tstart ranges from 100° C. to 1000° C.

19. The system of claim 15 or 16, wherein the temperature increment (ΔT) ranges from 0° C. to 200° C., and wherein biomass moisture content is less than 15%.

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20. The system of claim **17**, wherein

the dehydration catalyst comprises any acid catalyst or combination of acid catalysts, or

the aromatization catalyst is selected from the group consisting of MFI type zeolites and metal modified MFI-type zeolites including one or more metals selected from the group consisting of: Group VIB metals, Group VIIB metals, Group VIII metals, Group IB metals, Group IIB metals, Ga, and In, or

the gas-upgrading catalyst comprises one or more metal modified MFI type zeolites including one or more metals selected from the group consisting of: Ga, Zn, In, Mo, W, Cr, Pt, Pd, Rh, Ru, Au, and Ir.

21. The system of claim **16**, wherein a sequence of catalysts is determined by renewable fuel yield or by temperature of devolatization of biomass components, and wherein one or more biomass source serve as feedstock for each processing station.

22. The method of claim **1** or **9**, wherein at least one processing station comprises an auger reactor.

23. The system of claim **15** or **16**, wherein at least one processing station comprises an auger reactor.

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